Oak Ridge National Laboratory

Development of Functionally Graded Transition Joints to Enable Dissimilar Metal Welds

FEAA-151

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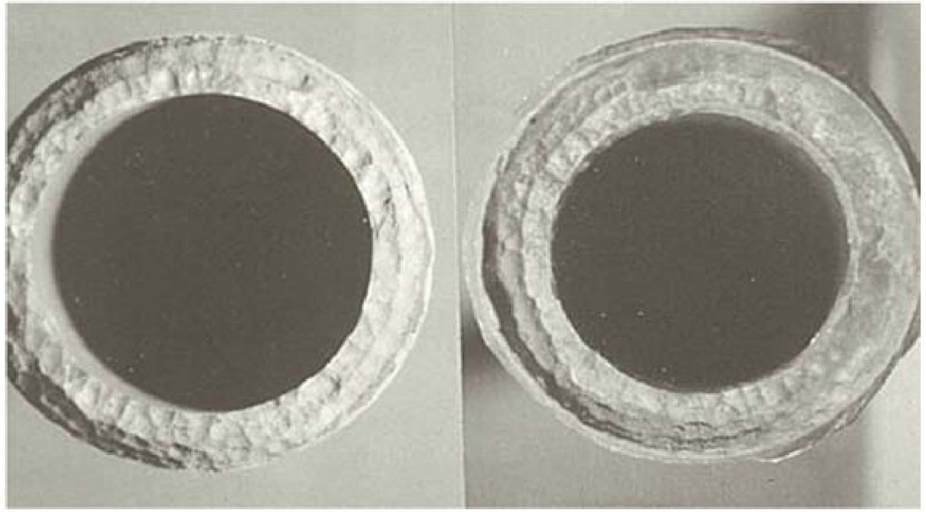
Transition Joints: Hybrid Materials in Power Generation

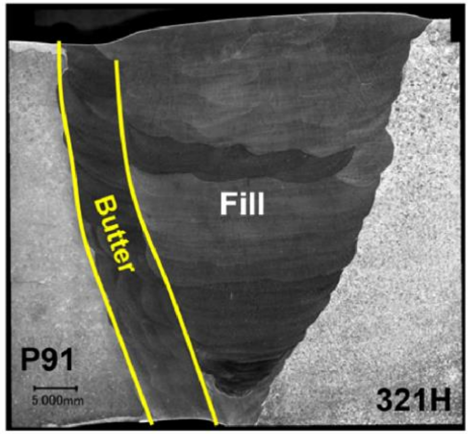
- Ferritic (cost-effective) and austenitic (high temperature performance) steels are used in power generation plants



- Challenges:
  - Coefficient of thermal expansion (CTE) mismatch
  - Carbon migration across the interface
- Mitigation:
  - Nickel based alloys used as weld filler material to mitigate CTE mismatch

Gauzzi & Missori, Journal of Mat. Sci., 1988

Seifert et al. 2016



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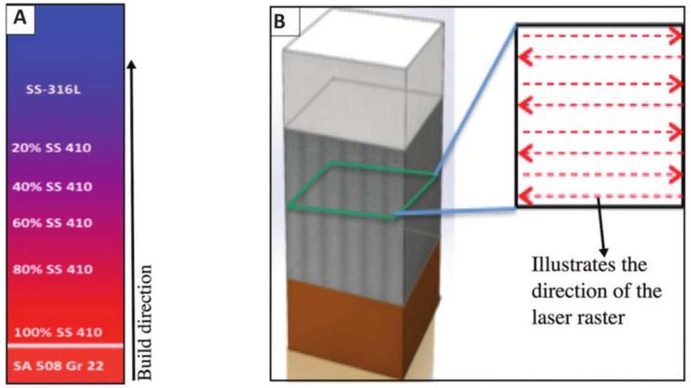
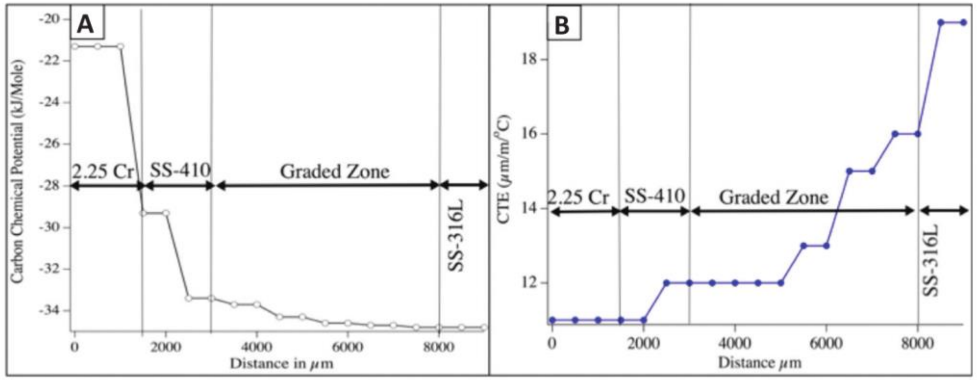
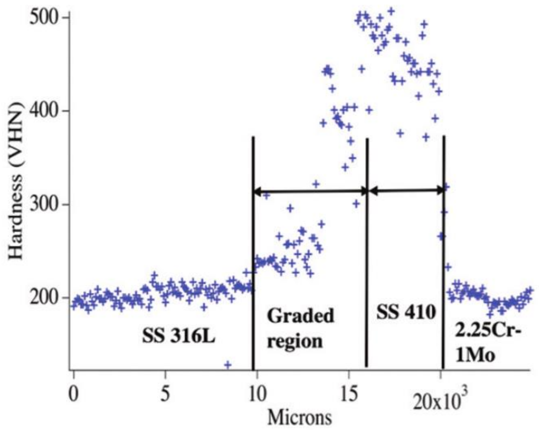
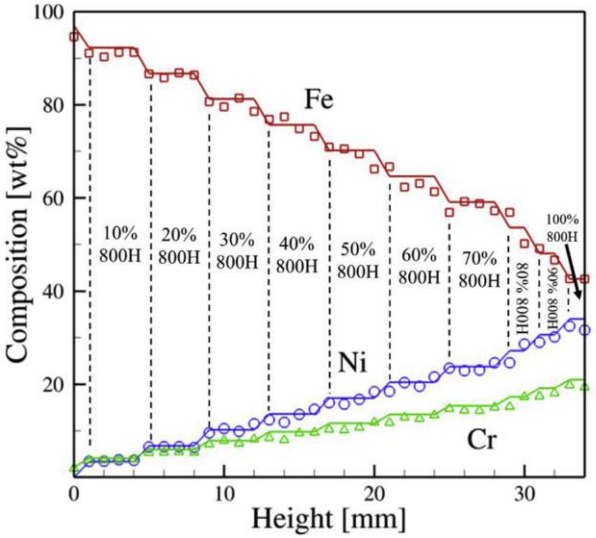
Transition Joints Enabled by AM: Continuum

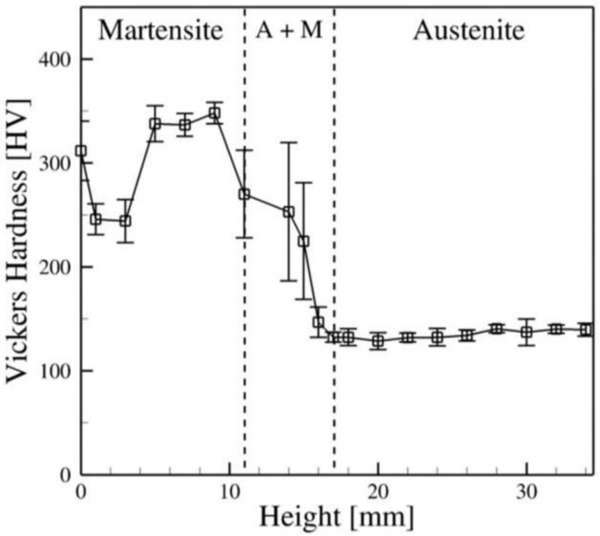






Sridharan et al. Welding Journal, 2017



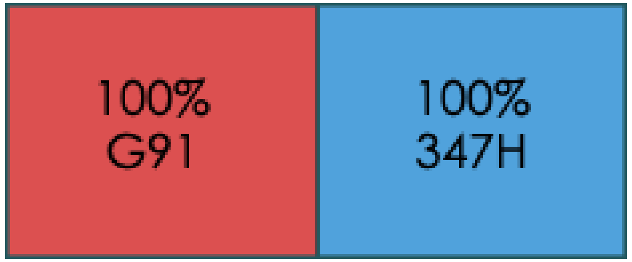


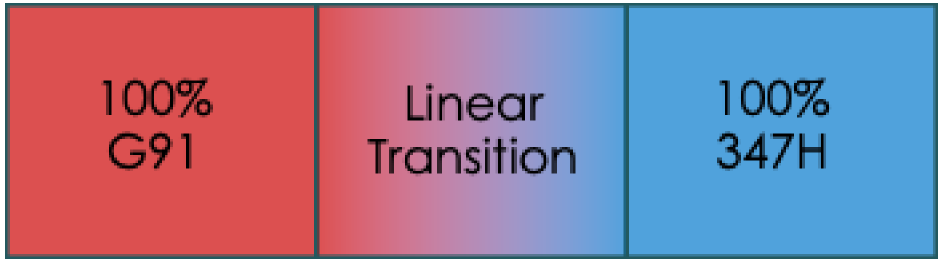
Zuback et al. Welding Journal, 2019

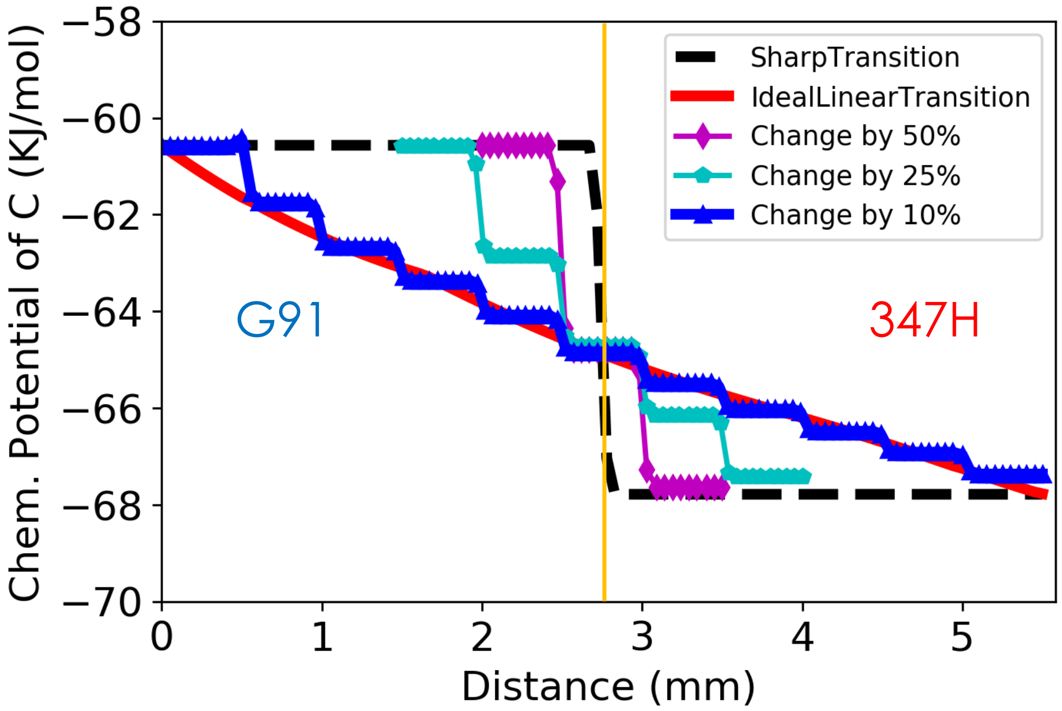
- ➢ Existing work focused on linear changes in composition
- ➢ Sridharan et al. reported an increase in hardness in the gradient region
- ➢ Zuback et al. observed a hardness gradient across the transition zone

Brentrup & DuPont, Welding Journal, 2013
Galler et al., Met Trans A, 2019
Subramanian et al., Welding in the World, 2021

Linear Grading: More Gradual Composition Change Results in Shallower Carbon Chemical Potential Gradient







Practical considerations change things

What is the minimum distance over which composition can be changed? (typically, ~2mm)

Keep the length of the transition zone as small as possible – AM is expensive still!

Is linear composition change the most efficient?

CALPHAD Design Approach

Equilibrium phase fraction evolution for each 10% composition variation using CALPHAD

→ Identify compositions where a drastic change in phase fraction evolution observed

→ Diffusion calculations during long term aging at service conditions (650 °C, for 100,000 hours)

CTE estimation for each 10% composition variation using CALPHAD

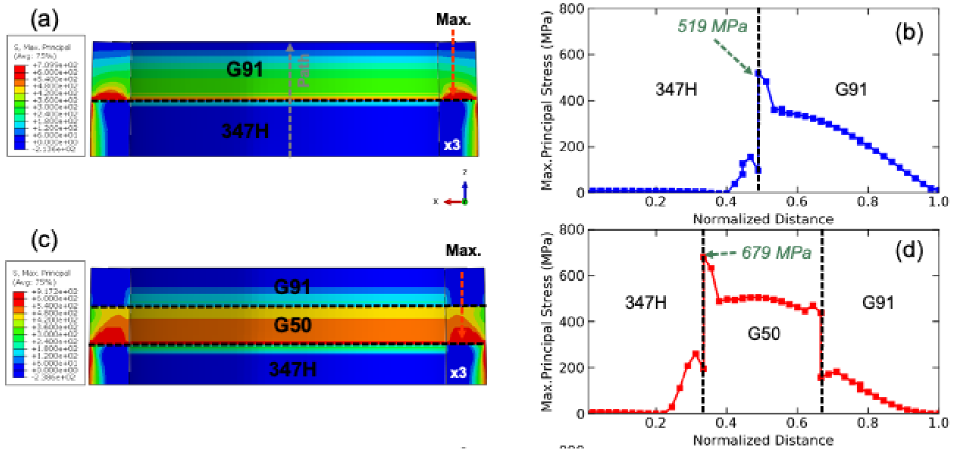
↔ Finite element modeling for residual stresses due to CTE variations

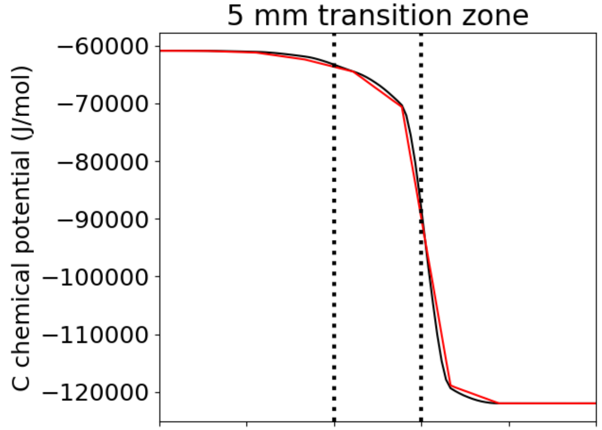
Configuration with minimum peak principal stress

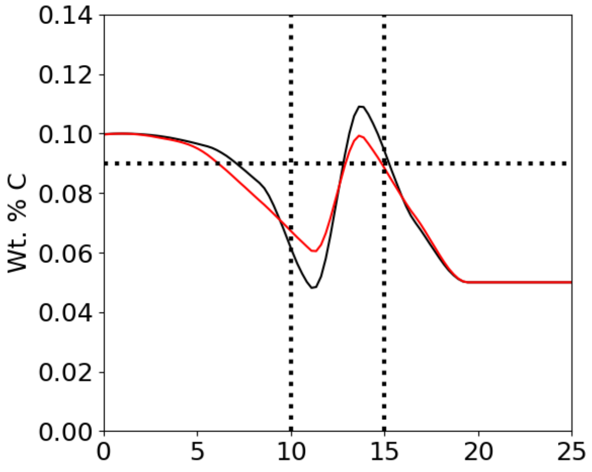
Configuration with shallower C chemical potential gradient and C depletion at interface

Optimal transition zone design

Fabrication of graded transition joints using DED

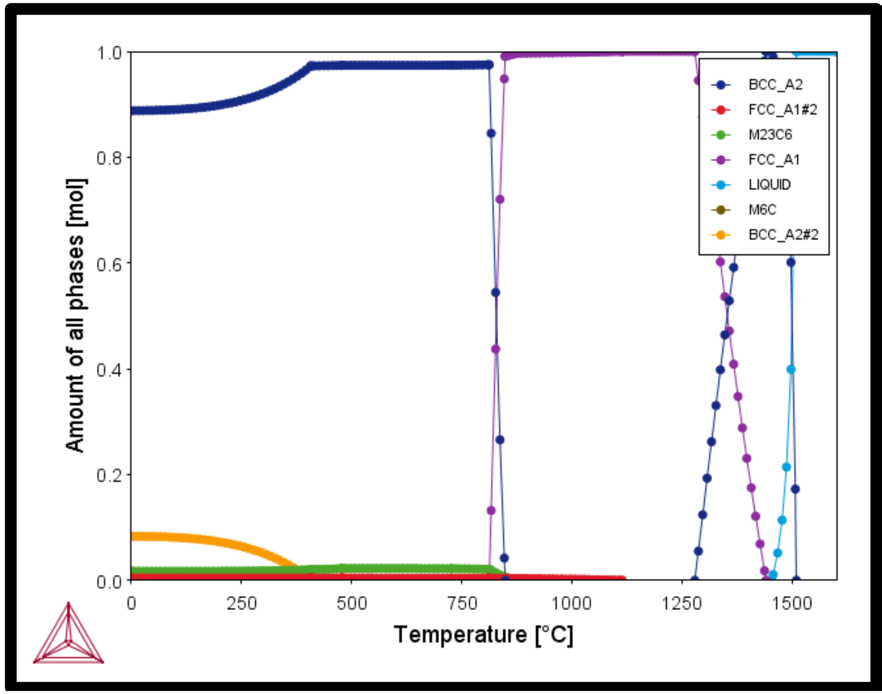




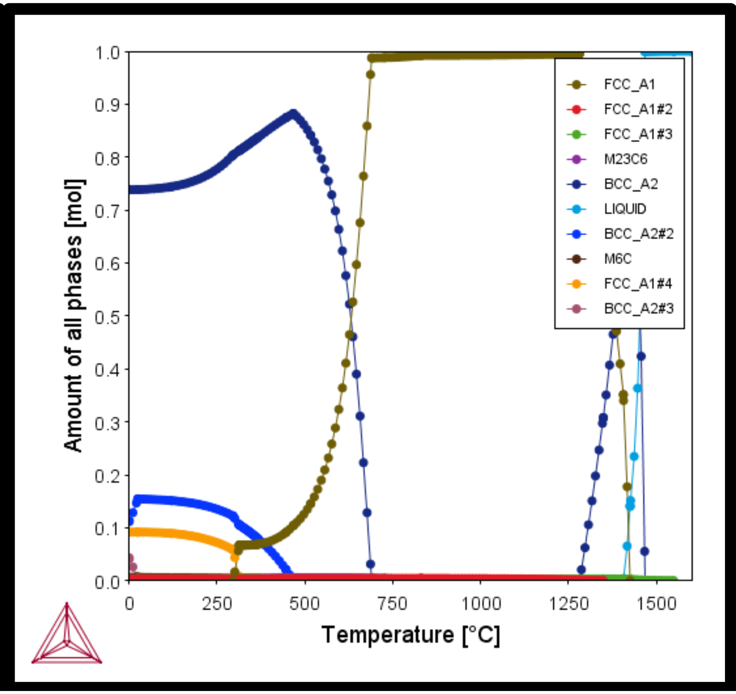


How To Decide Composition Changes?

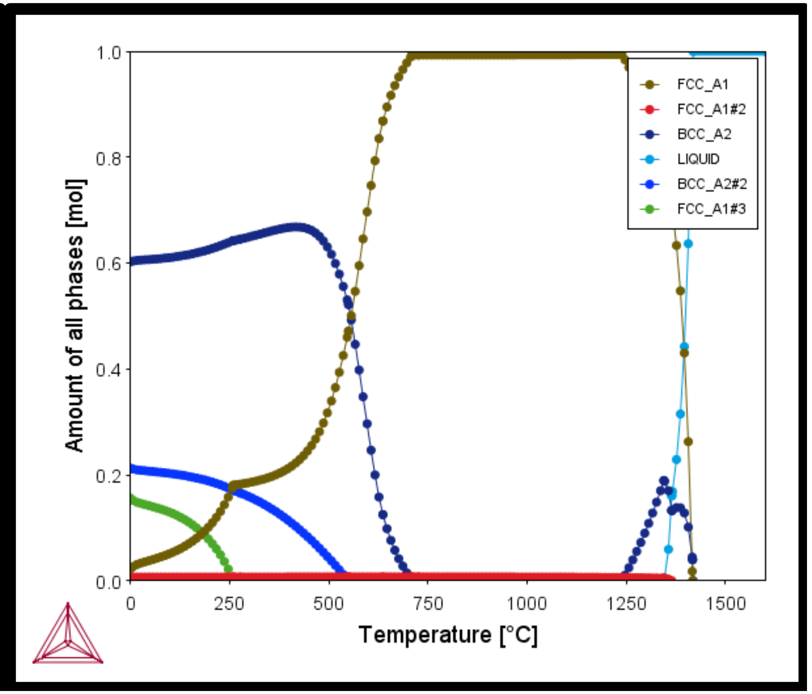
100 % Ferritic – Base material



50 % Ferritic



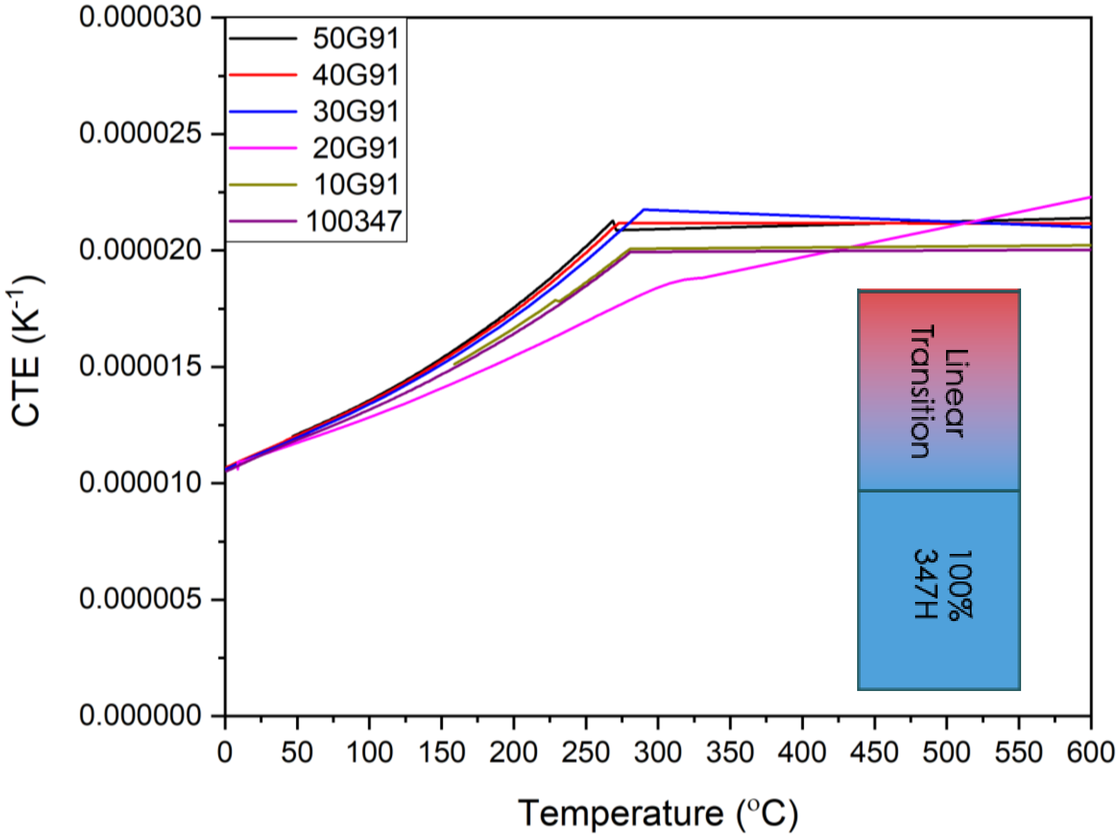
100 % austenitic – Base material



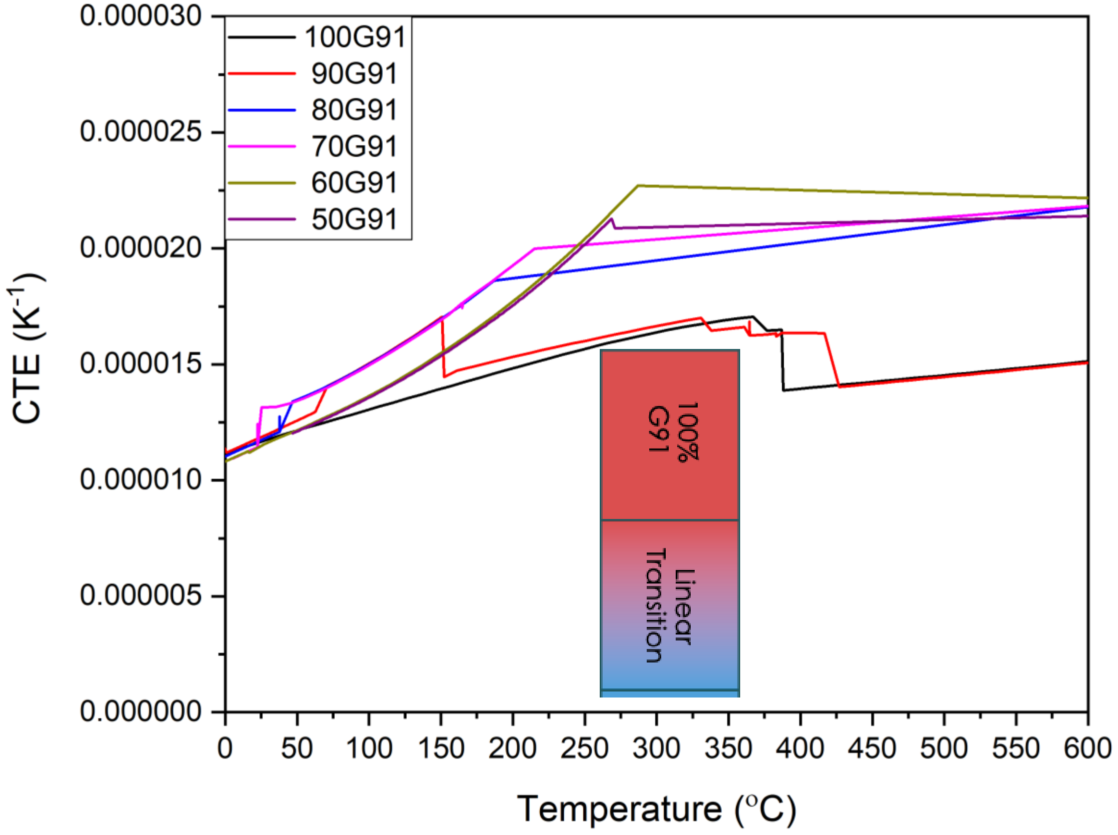
Equilibrium calculations conducted at every 10% step and phase fractions determined

Variations in coefficient of thermal expansion calculated at each step

Step Change in CTE Variations Advice Composition of the Transition Zone

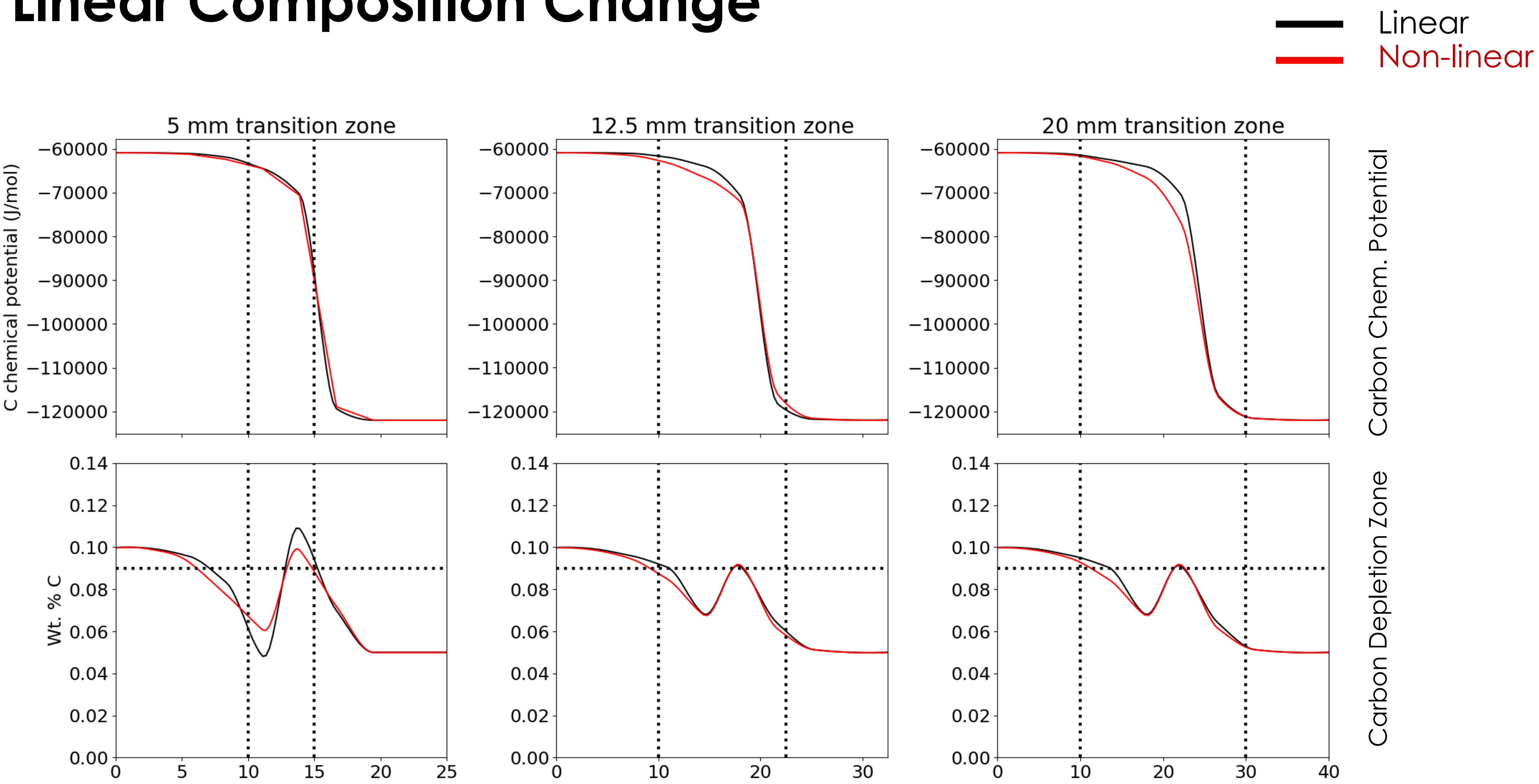


CTE Changes Transitioning Away from 347H

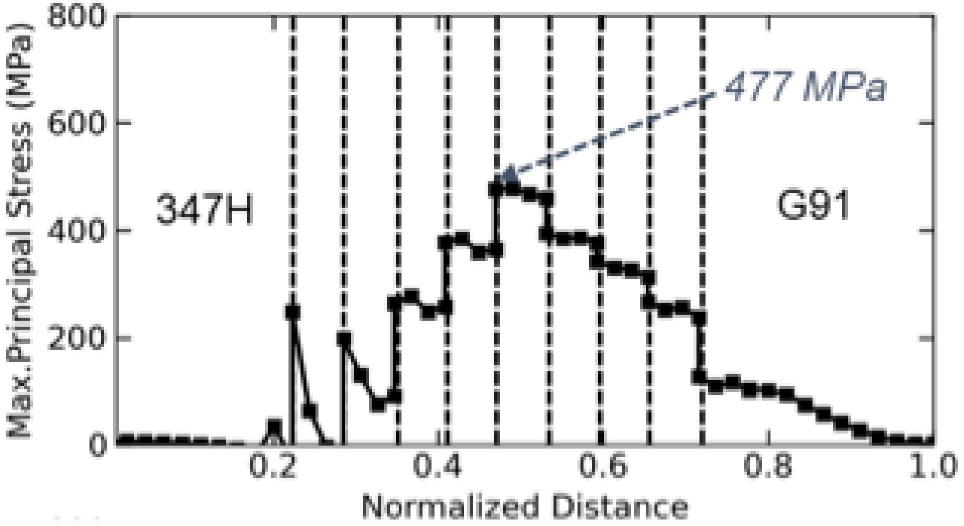


CTE Changes Transitioning Away from G91

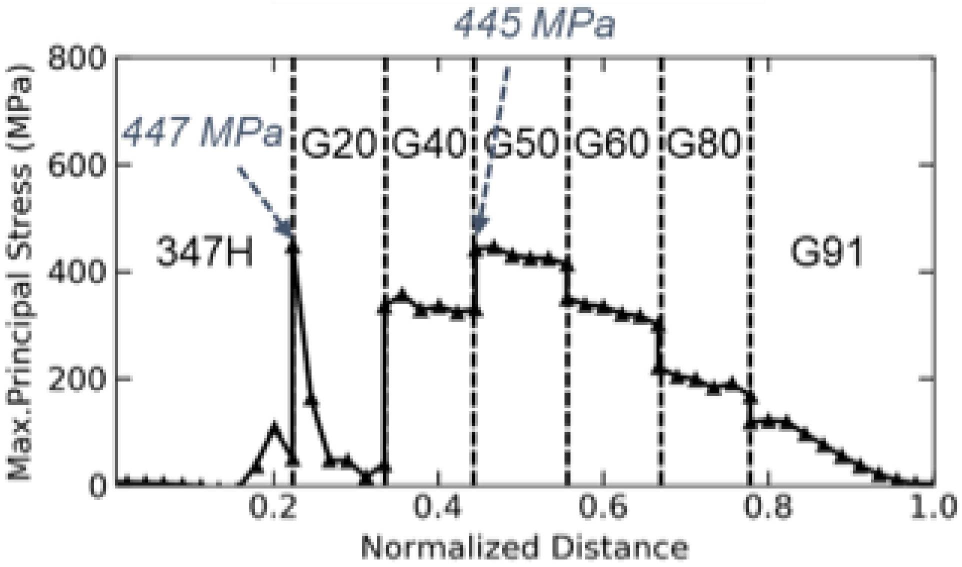
Carbon Chem. Potential & Depletion Zone Lower for Non-Linear Composition Change



Lower Residual Stress in Non-Linear Transition Joint

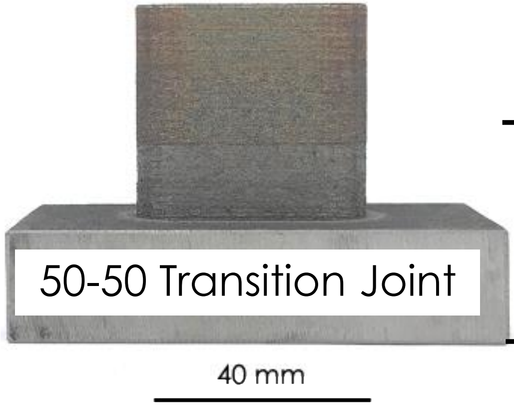


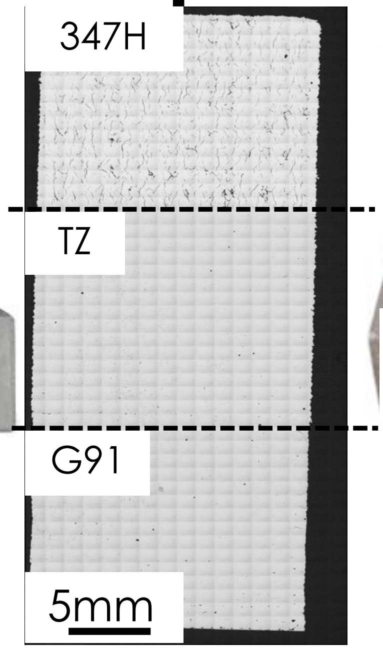
Linear composition Change

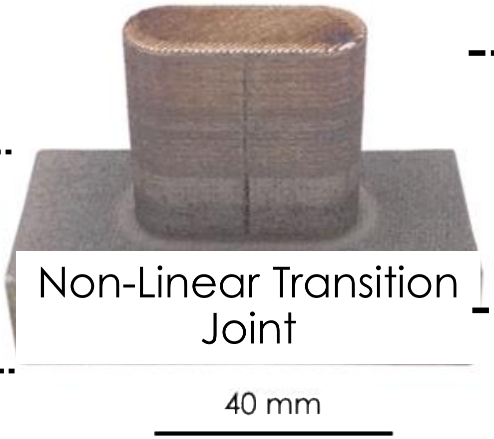


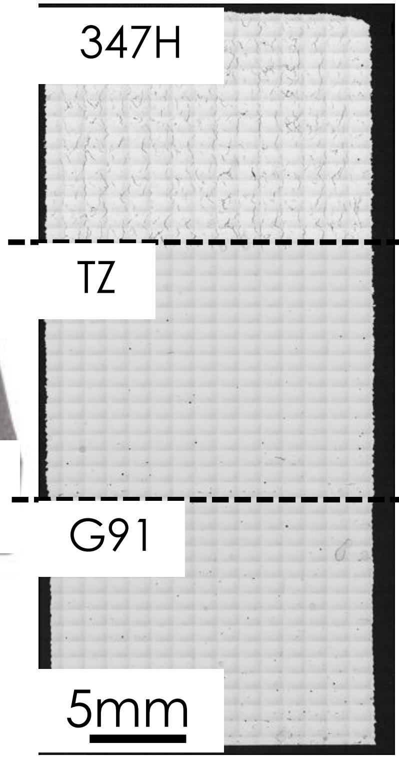
Non-Linear composition Change

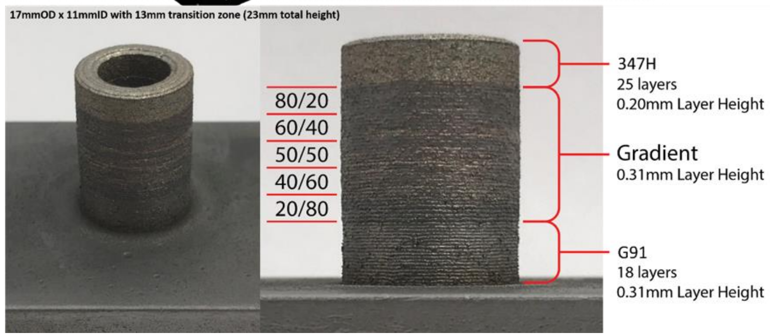
Fabrication of Transition Joint Samples







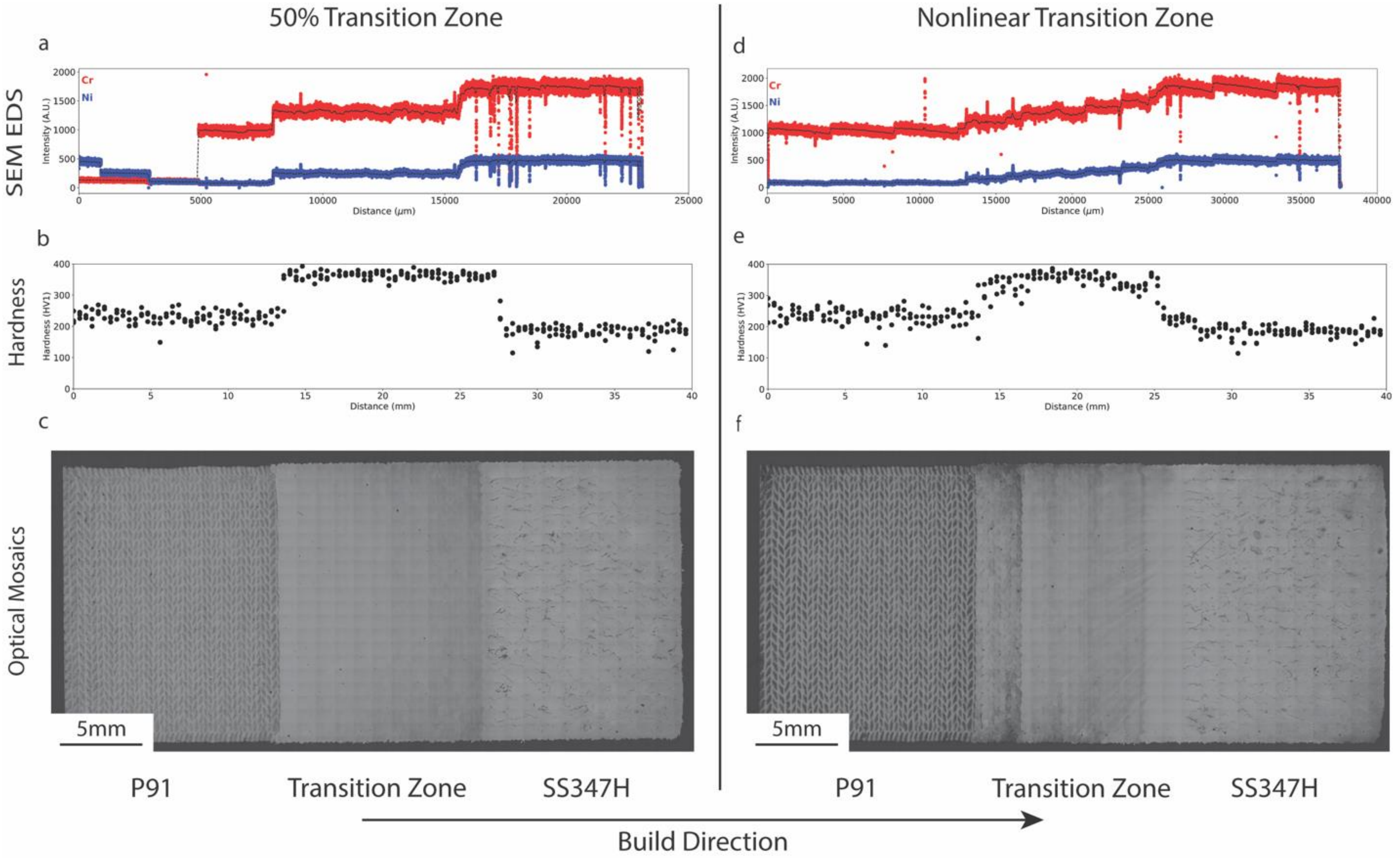




OD: 17mm
ID: 11mm
Total Height: 23mm

- Transition joints deposited using a BeAM Modulo 400 Blown Powder AM system
- Joints deposited with 50/50 (3 sections) transition zone or a gradation of 80/60/50/40/20 (7 sections)
- Cracking observed in 347H but not in the transition zone or G91
- Tubular geometry deposited and currently under evaluation for understanding geometry impacts on defects and microstructure

Characterization of the Fabricated Joints

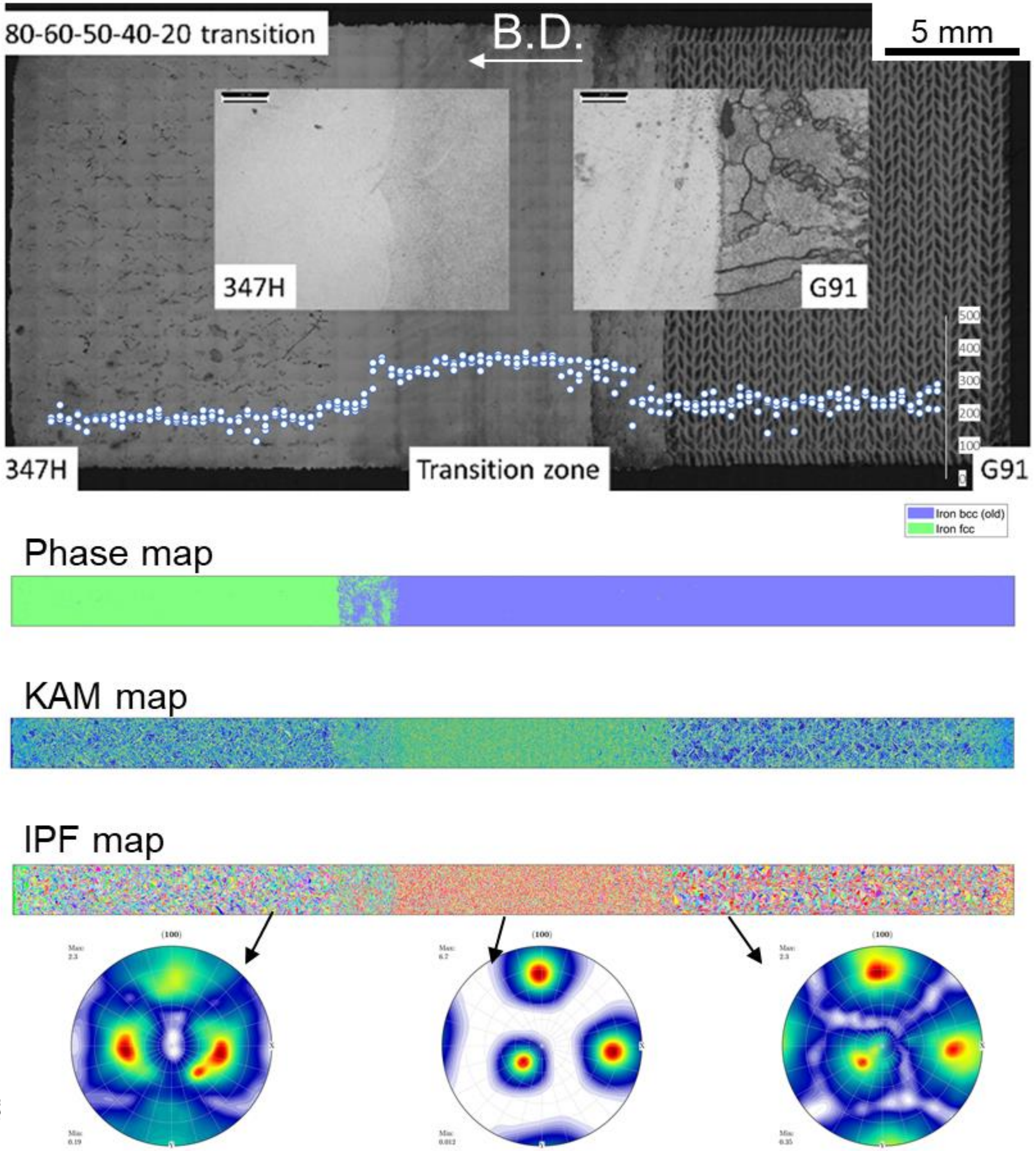


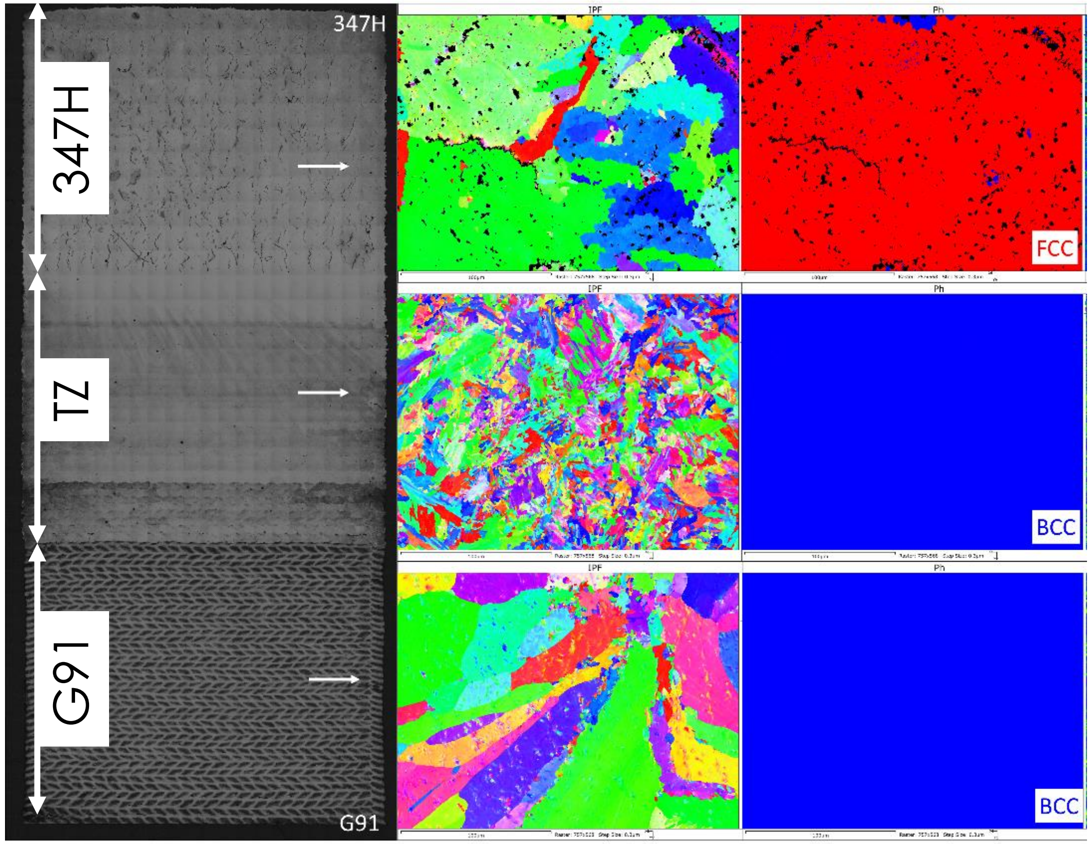
Gradual change in composition

Higher hardness in the transition zone

Cracking in the 347H section

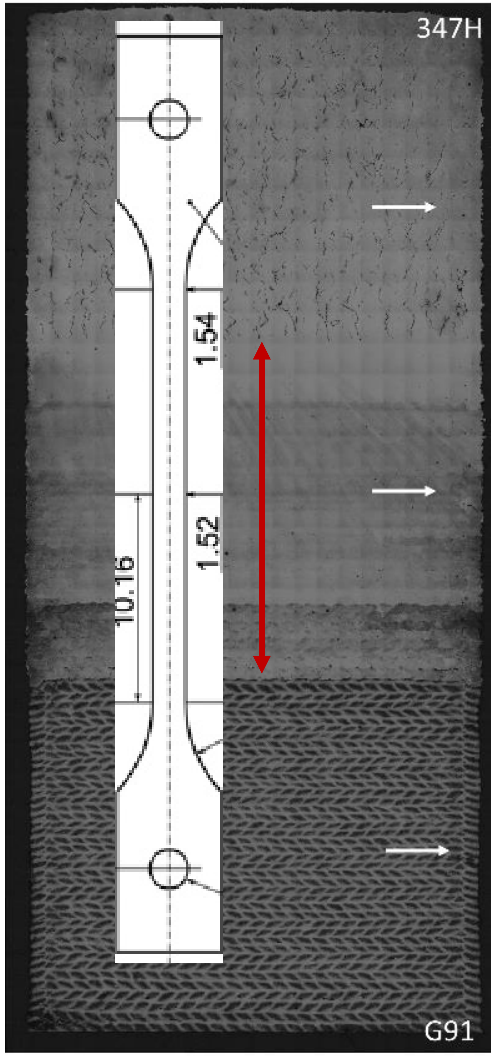
Characterization of the Non-Linear Joint

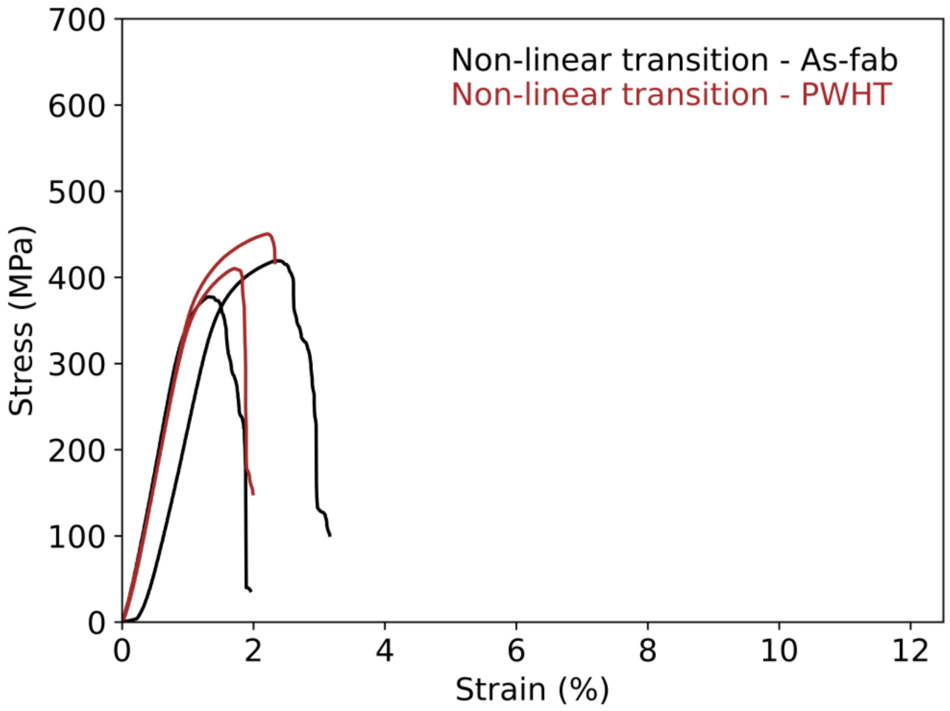




- In the 80%347H-20%G91 region, dual phase region exists
- Significant microstructural refinement in the transition zone

Tensile Behavior of Composite Structure in As-Fab and PWHT Condition





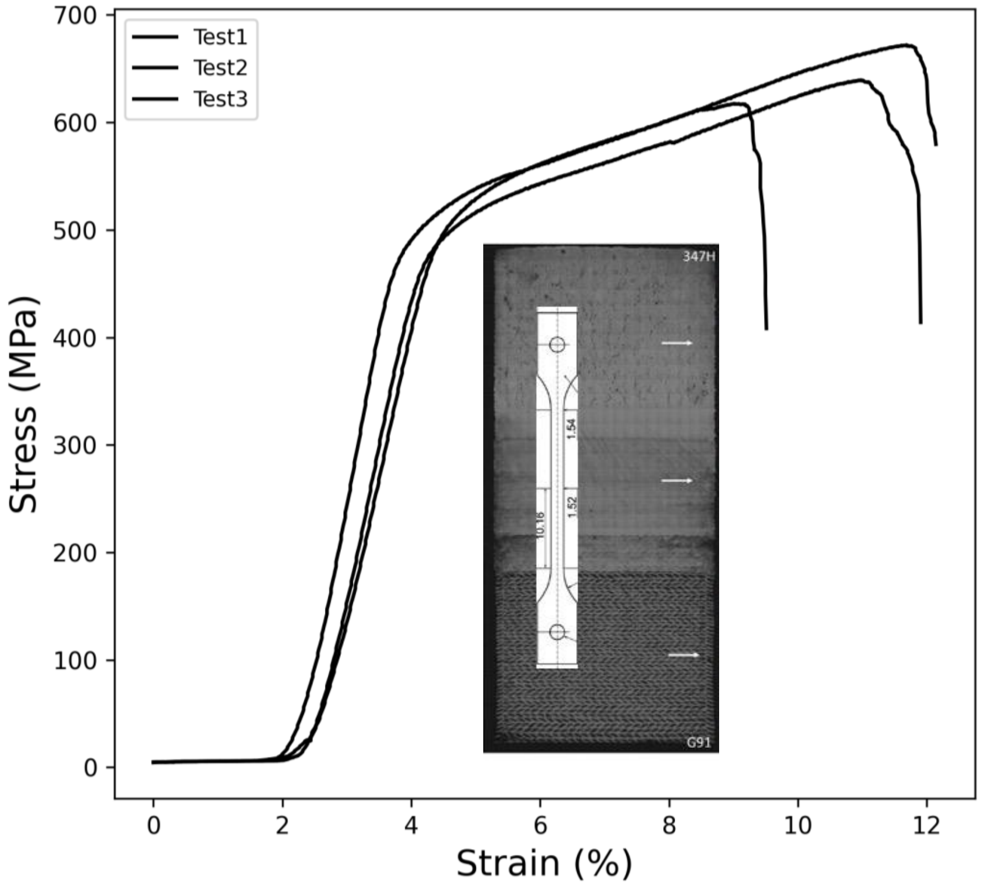
Gage length contained transition zone as well as base metal regions from SS347H and G91 steels

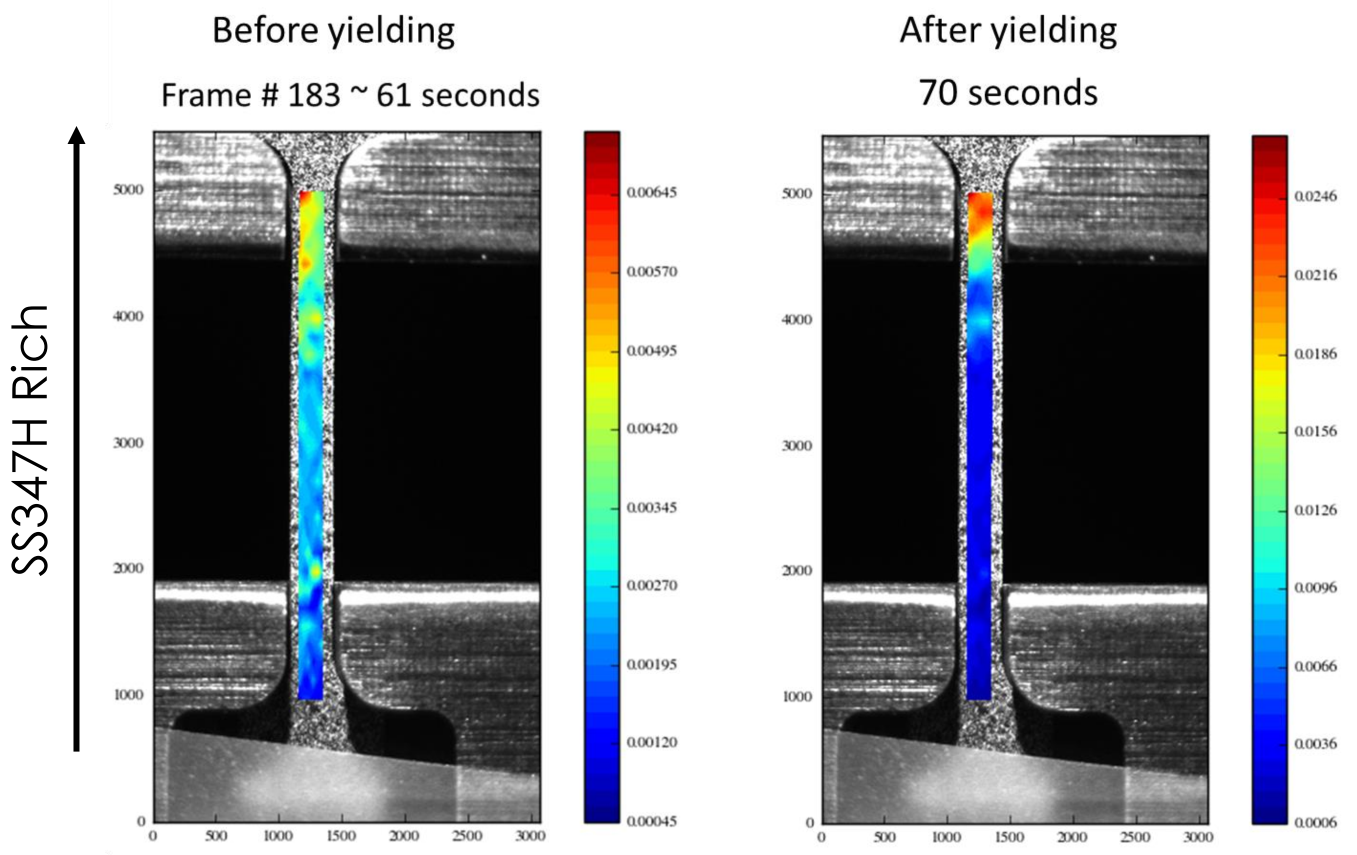
PWHT conducted: 750 °C for 45 min followed by air cooling

Cracks in SS347H region result in lower elongation to failure

No difference between as-fab and PWHT conditions

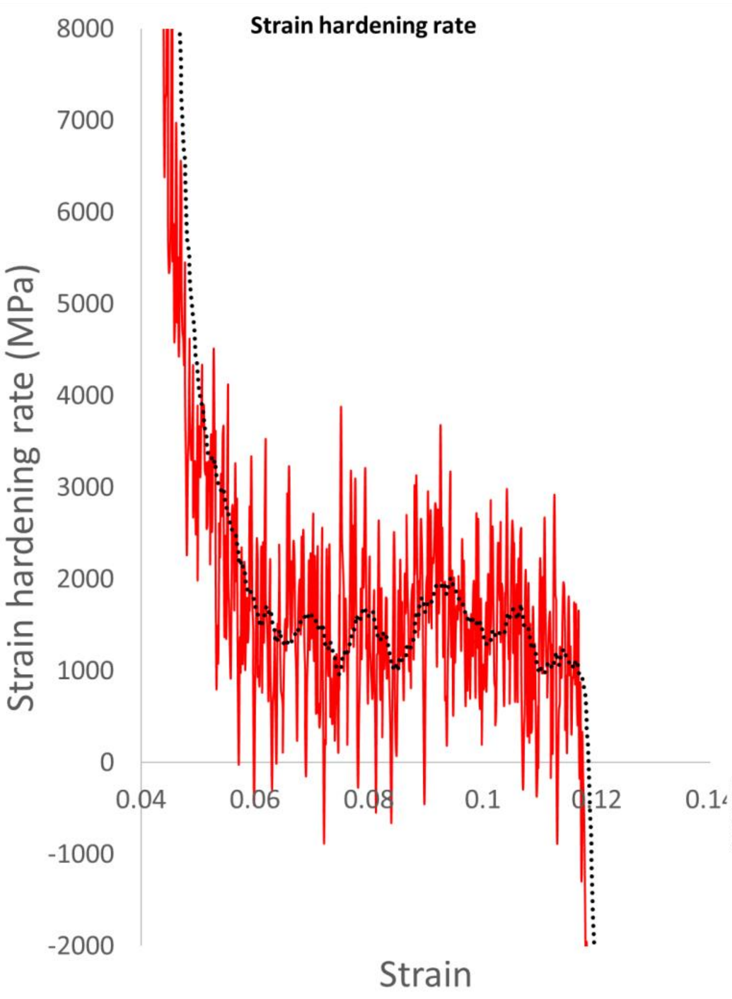
Strain Localization Near the SS347H Region

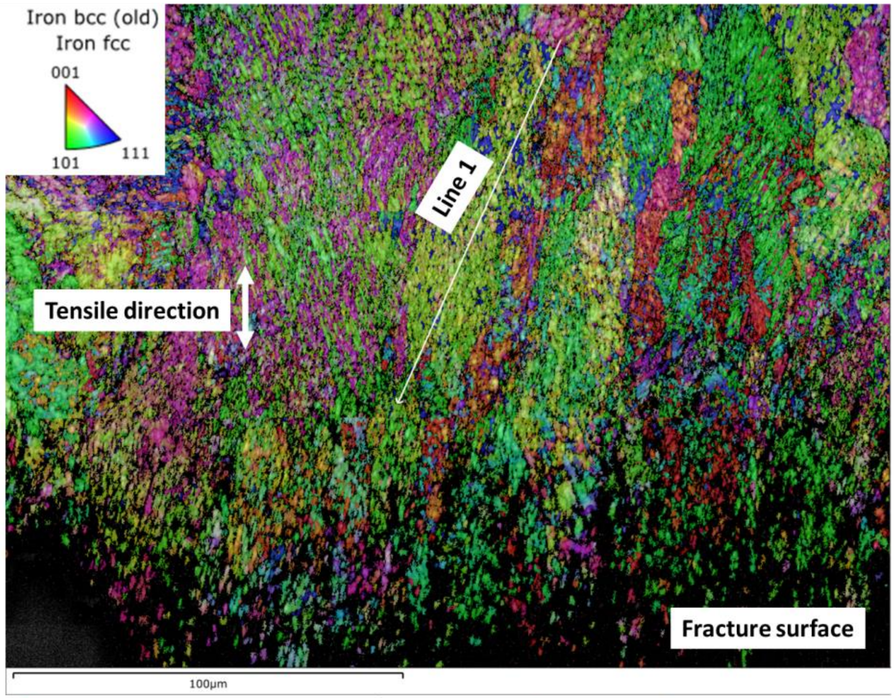


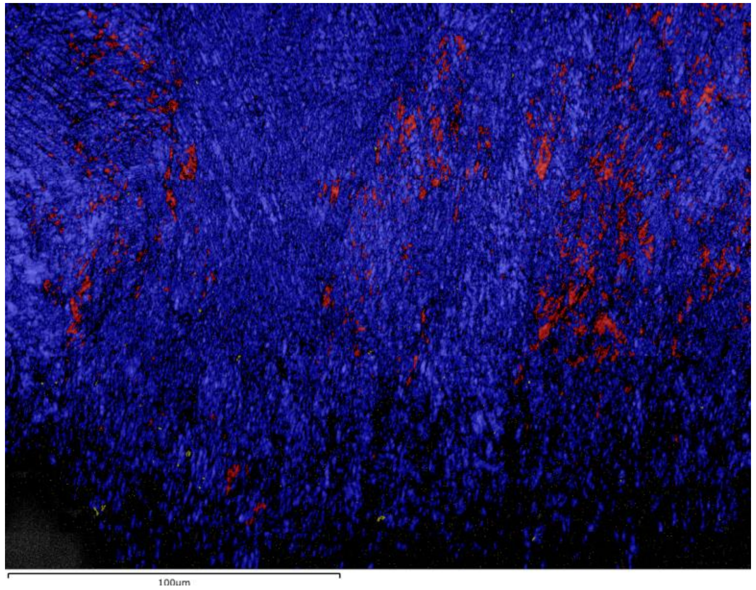


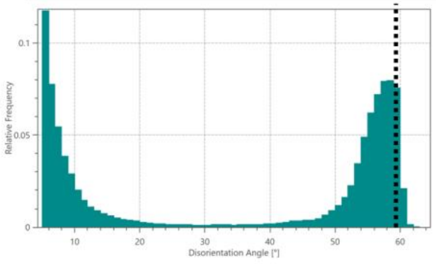
- ➢ Tensile **sample extracted from the transition zone**
- ➢ Strain localization in the 80%SS347H-20%G91 region

Significant Strain Hardening and Twinning in the Failed Section

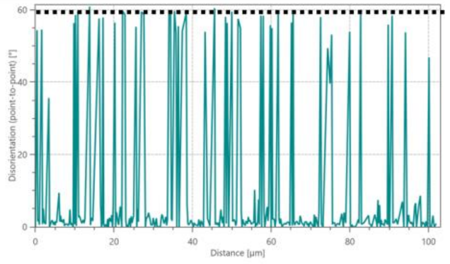








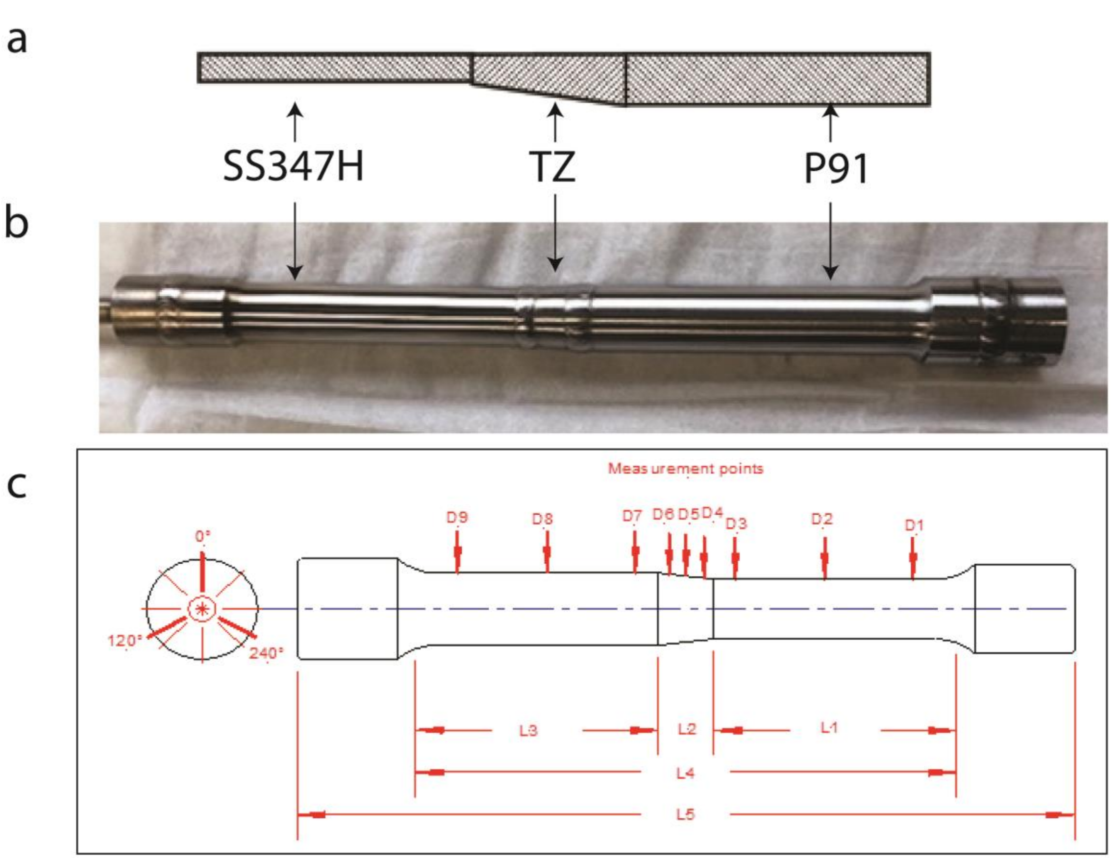
Grain boundary misorientation distribution

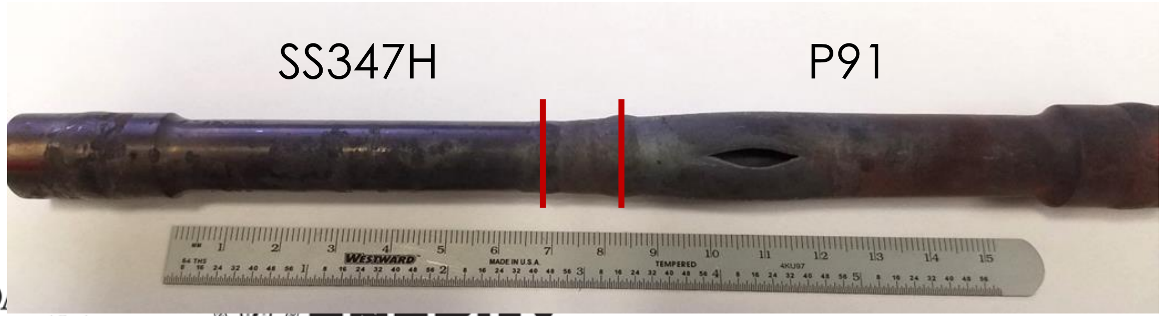


Line 1 misorientation

Failure occurs in the dual-phase region near the SS347H side of the joint

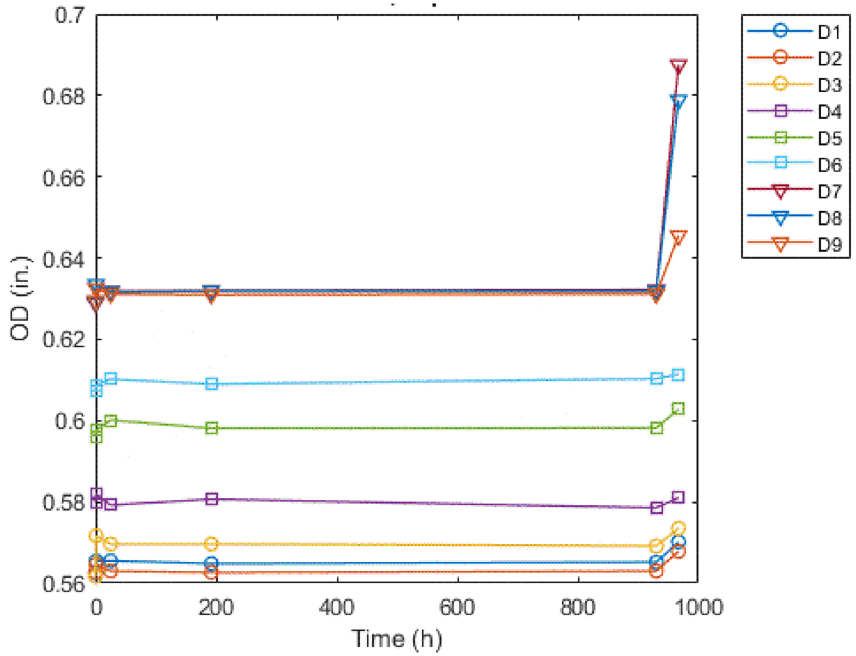
Pressurized Tube Creep Testing





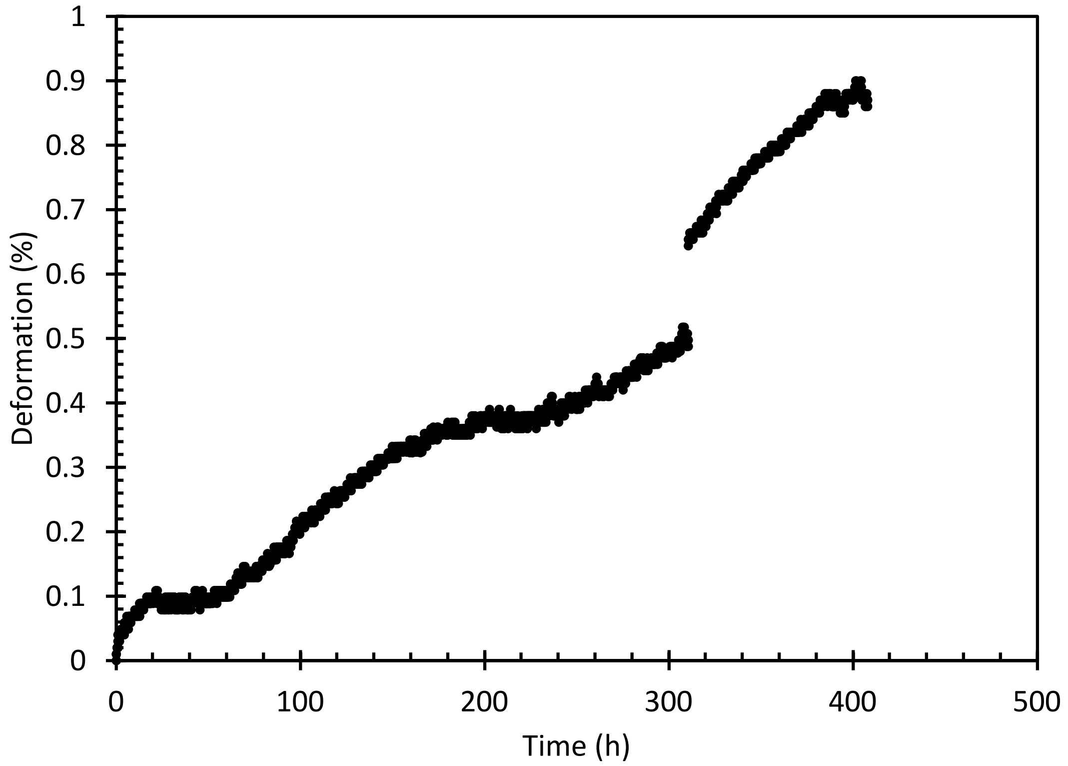
Different cross-section thicknesses used to equate rupture time in all sessions

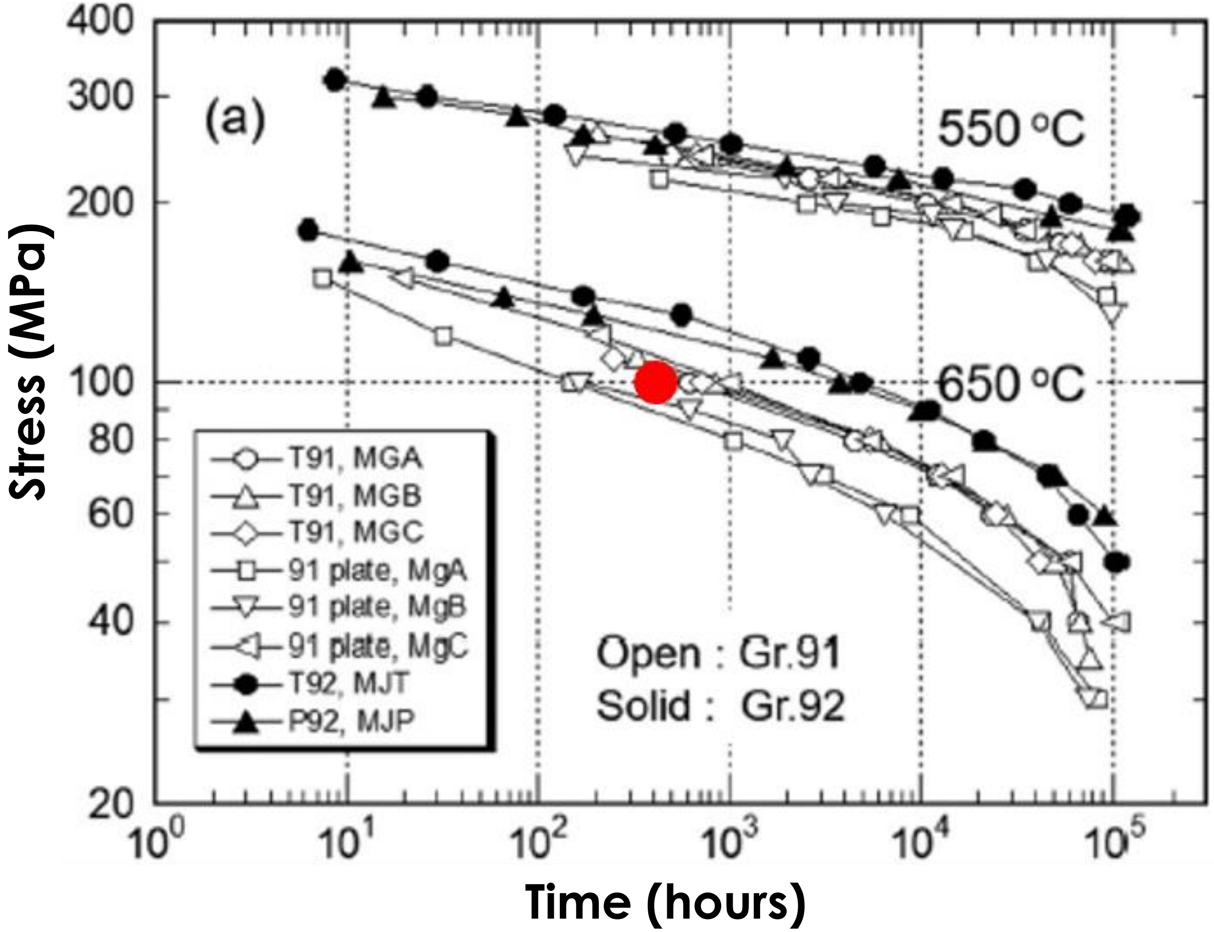
Measured strains were the highest in G91 section and eventually caused failure



No	Temp (C)	P (psi)	P (MPa)	T_inc (h)	T_acc (h)
1				0	0
2	650	6,710	46.25	1	1
3	600	6,680	44.06	24	25
4	400	6,680	44.06	167	192
5	400	6,680	44.06	738	930
6	650	6,710	46.25	37	967

Ongoing Creep Test at 100 MPa and 650 °C

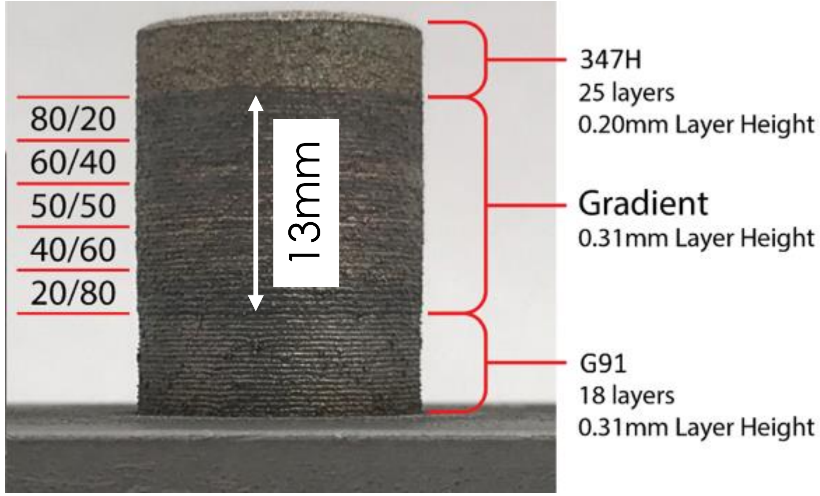


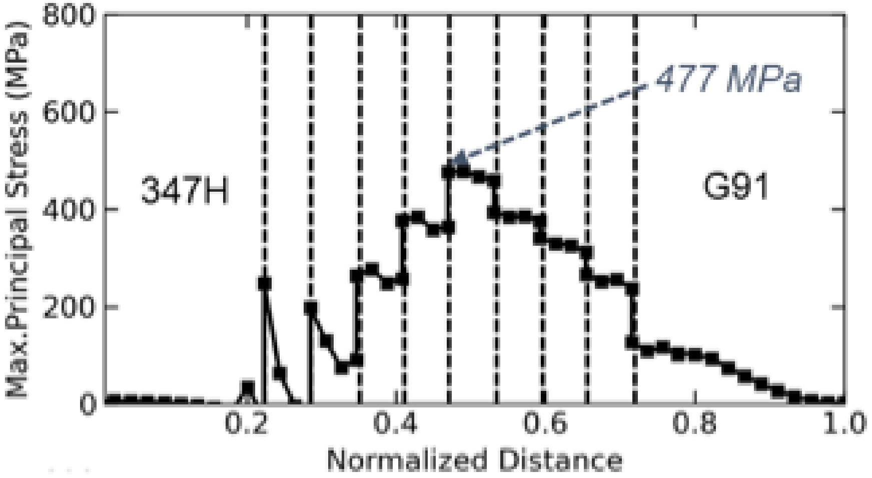


Sample tested in as fabricated condition

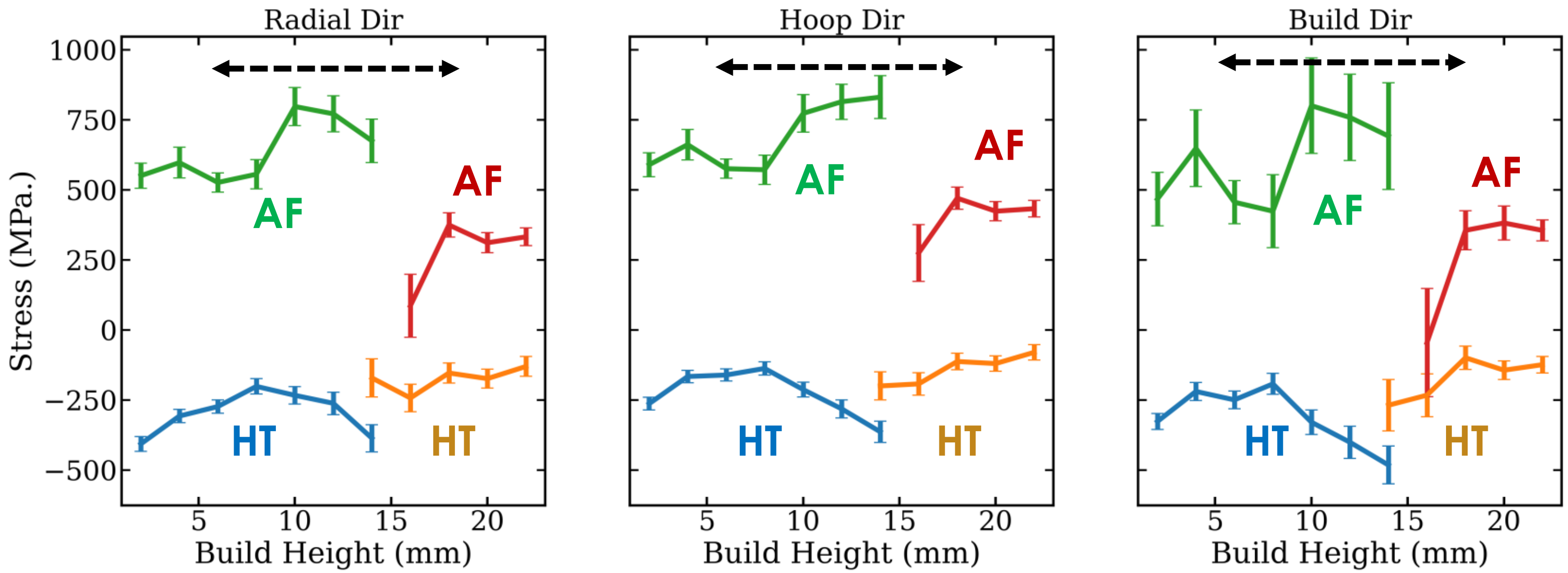
Test ongoing – comparable to conventionally fabricated Grade 91 alloy

Stress Evolution with Temperature





Conducted on a planar wall



- ➢ Residual stress is higher in as fabricated condition
- ➢ Stress reduces during HT (sample was heat treated to 650C and then cooled to room temperature)
- ➢ Stress changes from tensile to compressive upon heat treatment

Summary

- A linear gradient might not always have the lowest carbon chemical potential and carbon depletion
- Failure appears to occur via twinning in the zones closer to SS347H
- Residual stresses change from tensile to compressive when the sample is heat treated to 650 °C

Thank you

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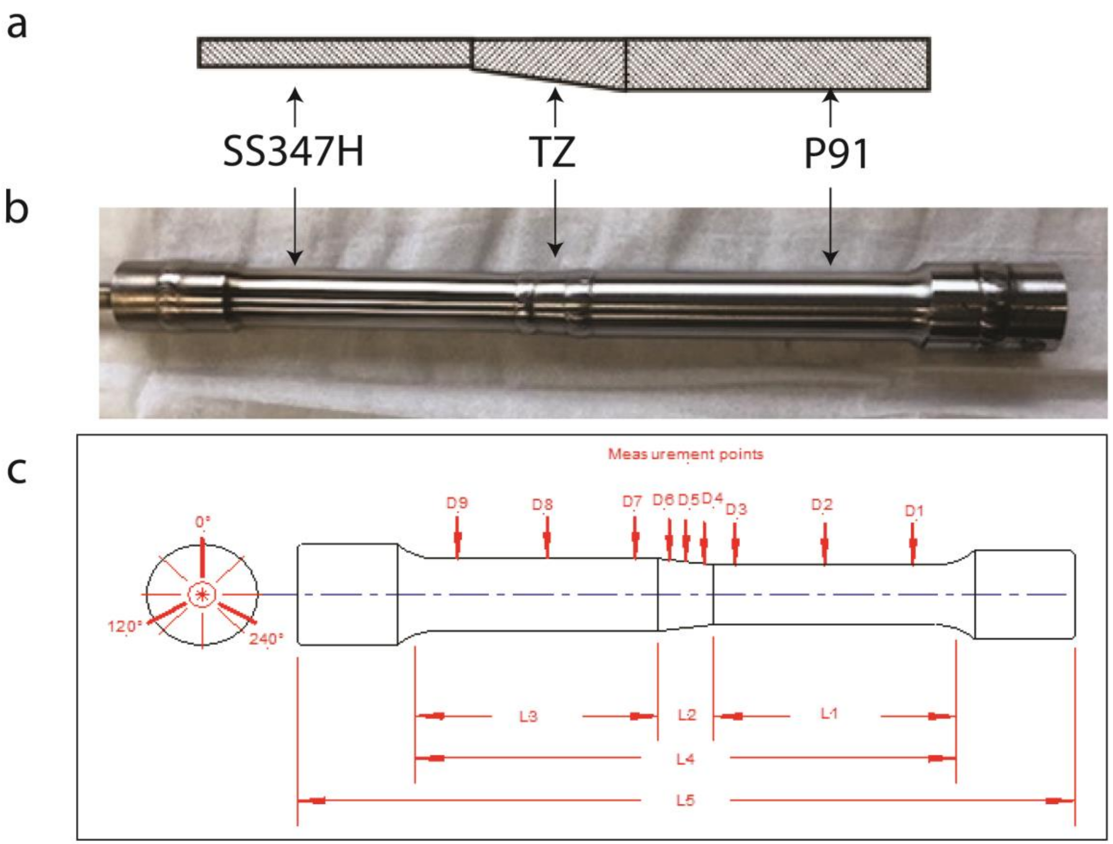
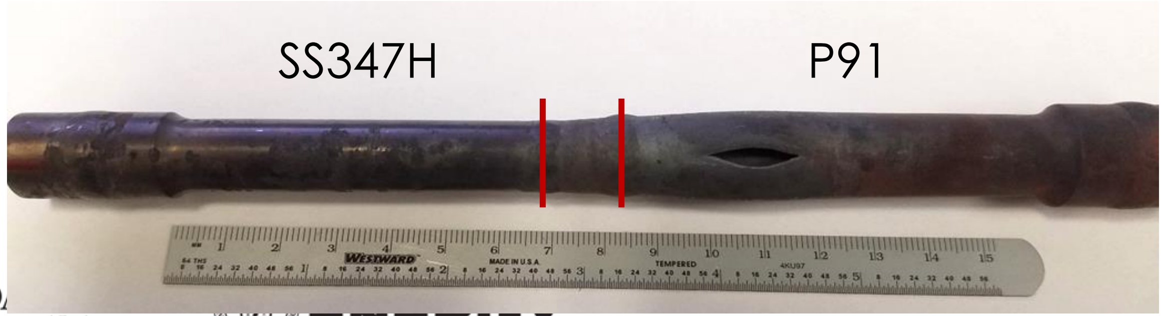
Pressurized Tube Creep Testing



Larson-Miller approach used to determine creep stress of 165MPa for SS347H and 103MPa for G91 for a stress rupture time of 500h at 650 °C

Therefore, different cross-section thicknesses used to equate rupture time in all sessions

Measured strains were the highest in G91 section and eventually caused failure



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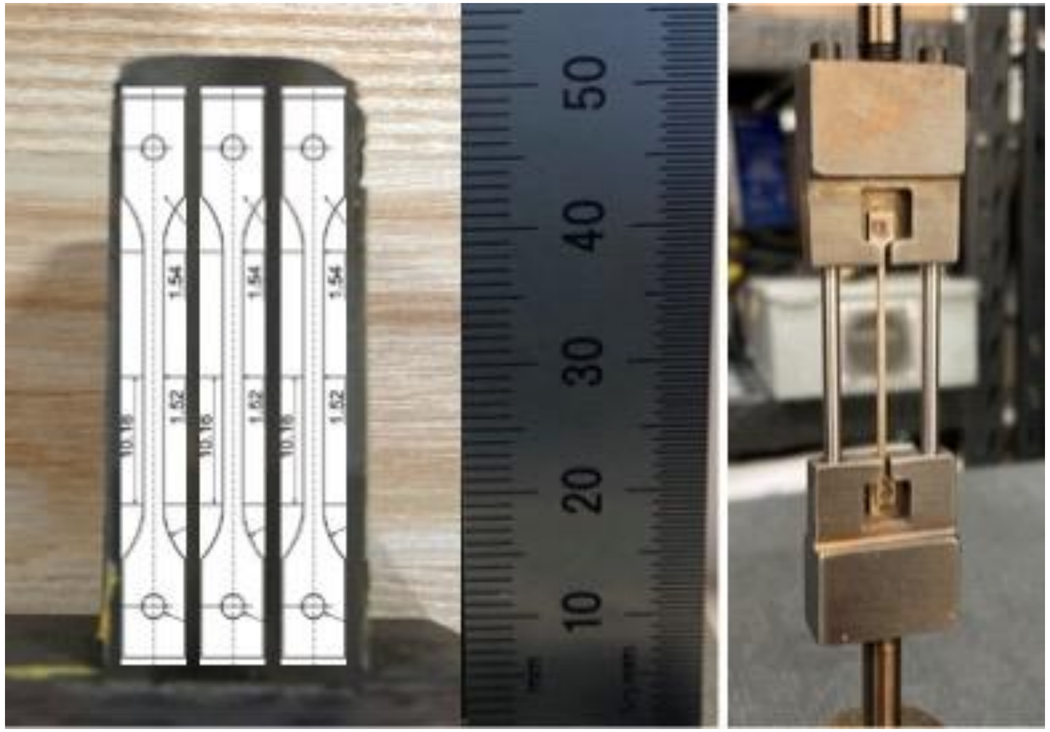
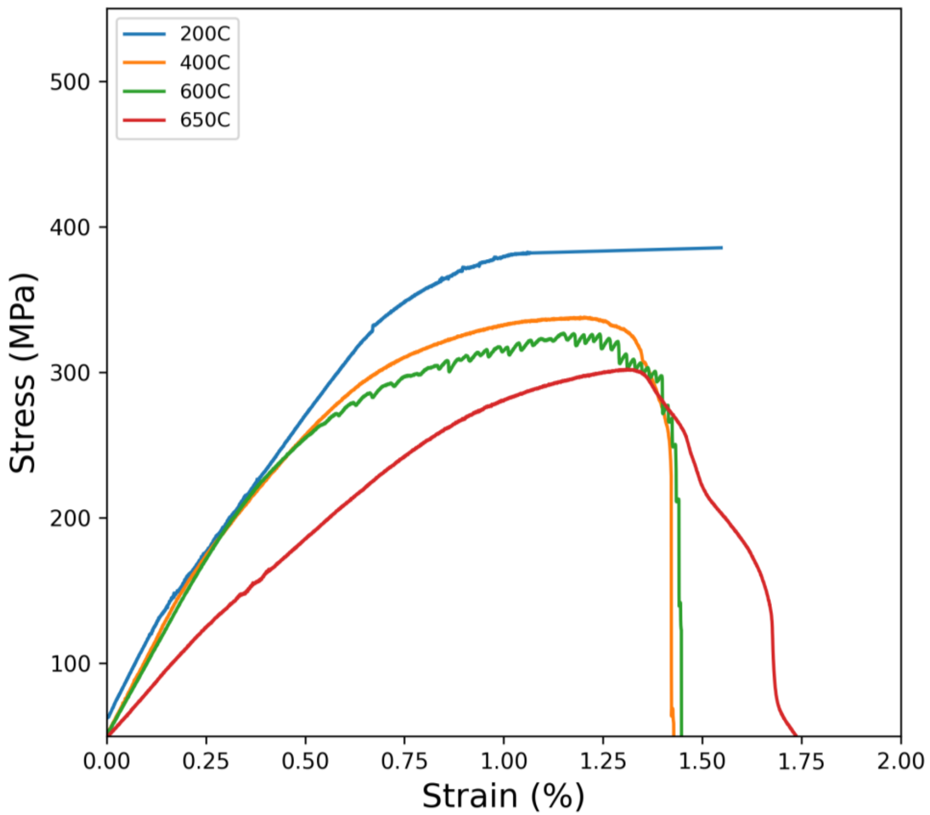
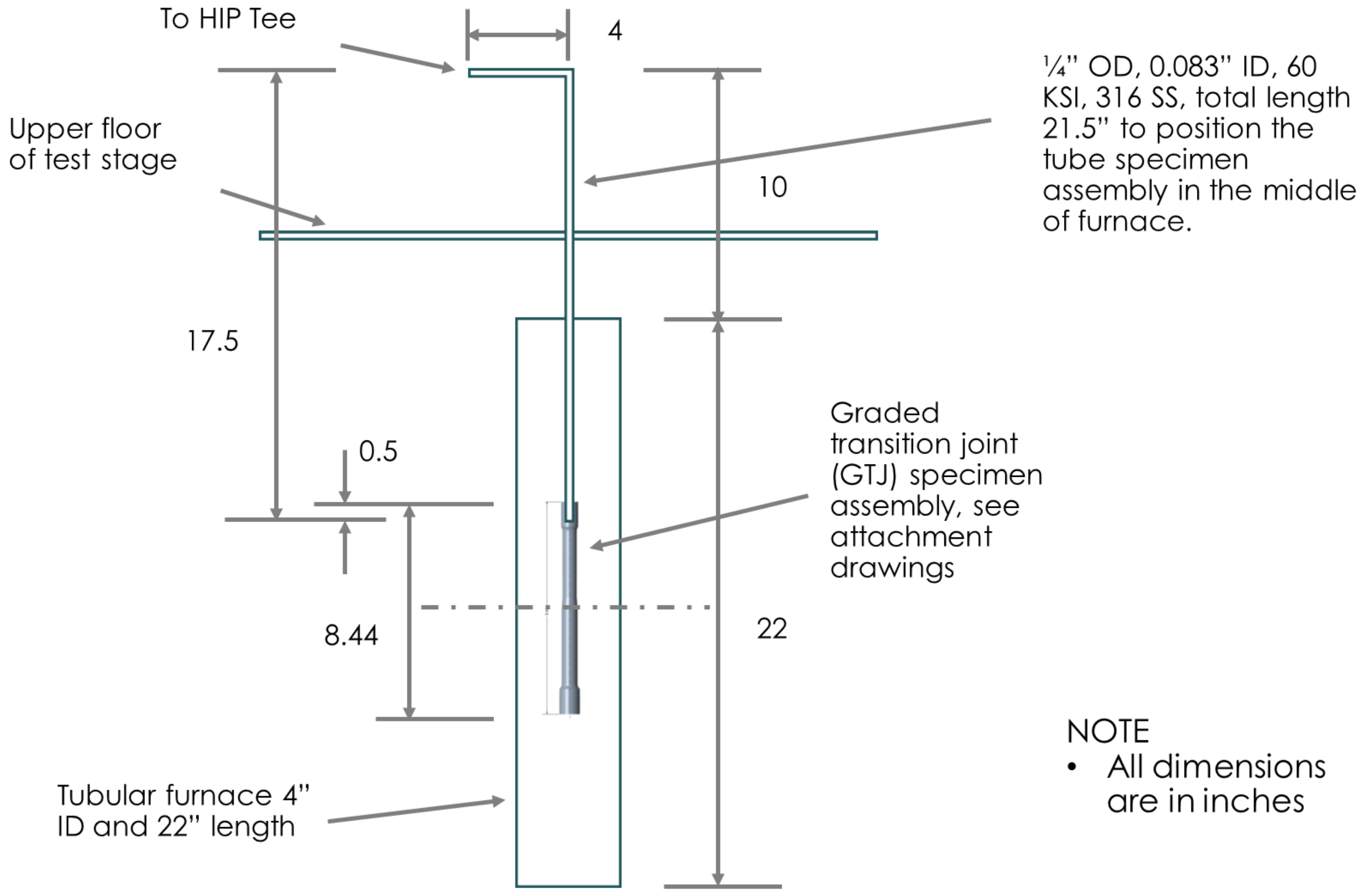
Tensile Behavior





Non-standard tensile samples extracted (SS1 gage length and SSJ3 grip geometry)

Enabled capturing transition zone as well as base material in the gage length



NOTE

- All dimensions are in inches